

VIII. *On the Intensity and Direction of the Force of Gravity in India.**By Lieut.-Colonel S. G. BURRARD, R.E., F.R.S.*

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[PLATES 14–20.]

(1.) *The Pendulum Observations of 1865–74.*

BETWEEN 1865 and 1873 observations were taken at 31 stations in India by Captains BASEVI and HEAVISIDE with the Royal Society's seconds pendulums. The results were published in Vol. V. of the 'Account of the Operations of the Great Trigonometrical Survey of India,' and have been subsequently discussed by many authorities.\*

Captain BASEVI expressed his results in terms of  $N$ , the number of vibrations of the mean pendulum observed in a mean solar day. The International Geodetic Association show their results in dynes, and it is desirable that we should follow their example. We have, therefore, to change the notation employed by our predecessors.

The fundamental formula, expressing the relation between the length of a pendulum, its time of vibration and the accelerating force  $g$ , is  $t = \pi \sqrt{l/g}$ . If  $N$  be the number of vibrations, which a pendulum of length  $l$  makes in a mean solar day of 86,400 mean time seconds, then

$$N = \frac{86400}{t} = \frac{86400}{\pi} \sqrt{\frac{g}{l}},$$

where  $t$  is the time of vibration.

If  $N$  becomes  $N + dN$ , when  $g$  becomes  $g + dg$ , then

$$\frac{N + dN}{N} = \frac{\sqrt{(g + dg)}}{\sqrt{g}}, \quad \text{or} \quad 1 + \frac{dN}{N} = \sqrt{1 + dg/g}.$$

By this formula, if certain values of  $N$  and  $g$  be adopted for a Standard Station, the results of the older pendulum observations can be converted, and the symbol  $g$  substituted for  $N$ .†

The pendulum observations in India were undertaken, and are now being extended, with the object of determining the difference between the force of gravity as observed

\* See 'Phil. Trans.,' A, vol. 186, 1895; HELMERT'S 'Die Schwerkraft im Hochgebirge'; HELMERT'S 'Höhere Geodäsie'; CLARKE'S 'Geodesy'; FISHER'S 'Physics of the Earth's Crust.'

†  $dg = 0.0226 dN$  is a rough rule, sufficiently accurate for many purposes.

at the standard stations of Europe and as observed in India; the determination of the absolute value of the force of gravity did not and does not form any part of the operations.

The values of gravity exhibited in Table I. are taken from Professor HELMERT'S Report to the International Geodetic Conference, which was held at Paris in 1900.

TABLE I.—BASEVI'S and HEAVISIDE'S Results Expressed in Dynes.

	Station.	Latitude.	Longitude.	Height H.	Observed value.	Correction for unevenness of ground.	$g \left(1 + \frac{2H}{R}\right) = g_0$	$g_0$ — attraction of the mass above sea-level = $g_0'$ .	Theoretical value.	$g_0' - \gamma_0$	$g_0 - \gamma_0$
					Metres.	$g$ centims.	$g' - g$	centims.	$\gamma_0$ centims.	centims.	centims.
Coast.	Punnae . . . . .	+ 8 9'5	+ 77 37'7	15	978'095	000	978'100	978'098	978'105	— 0'007	— 0'005
	Kúdankolam . . . . .	+ 8 10'4	+ 77 41'5	51	978'090	0	978'106	978'100	978'105	— 5	+ 1
	Minicoy . . . . .	+ 8 17'0	+ 73 0'0	2	978'191	0	978'192	978'191	978'108	+ 83	+ 84
	Alleppy . . . . .	+ 9 29'7	+ 76 17'6	2	978'166	0	978'167	978'166	978'141	+ 25	+ 26
	Mangalore . . . . .	+ 12 51'6	+ 74 49'6	2	978'231	0	978'235	978'234	978'257	— 23	— 22
	Madras Observatory. . . . .	+ 13 4'1	+ 80 15'0	8	978'237	0	978'239	978'239	978'266	— 27	— 27
	Cocanáda . . . . .	+ 16 56'4	+ 82 15'2	3	978'447	0	978'448	978'447	978'441	+ 6	+ 7
	Colaba Observatory (Bombay) . .	+ 18 53'8	+ 72 48'8	11	978'605	0	978'608	978'607	978'545	+ 62	+ 63
Inland.	Mallapatti . . . . .	+ 9 28'8	+ 78 0'8	88	978'091	0	978'118	978'108	978'141	— 33	— 23
	Pachapalliam . . . . .	+ 10 59'7	+ 77 37'5	296	978'084	0	978'175	978'140	978'189	— 49	— 14
	Bangalore, South. . . . .	+ 13 0'7	+ 77 35'1	950	977'998	0	978'289	978'179	978'263	— 84	+ 26
	Bangalore, North. . . . .	+ 13 4'9	+ 77 39'3	917	978'018	0	978'209	978'193	978'266	— 73	+ 33
	Namthábad . . . . .	+ 15 5'9	+ 77 36'5	358	978'207	0	978'318	978'275	978'352	— 77	— 34
	Kodangal . . . . .	+ 17 8'0	+ 77 38'5	584	978'233	0	978'461	978'394	978'451	— 57	+ 10
	Damargida . . . . .	+ 18 3'3	+ 77 40'1	593	978'283	0	978'464	978'396	978'499	— 103	— 35
	Somtana . . . . .	+ 19 5'0	+ 77 39'3	522	978'402	+ 1	978'563	978'502	978'555	— 53	+ 8
	Badgaon . . . . .	+ 20 44'4	+ 77 36'6	342	978'539	0	978'642	978'603	978'651	— 48	— 9
	Calcutta, Survey Office . . . . .	+ 22 32'9	+ 88 21'5	6	978'776	0	978'778	978'777	978'764	+ 13	+ 14
	Ahmadpúr . . . . .	+ 23 36'4	+ 77 40'9	516	978'874	+ 2	978'832	978'774	978'833	— 59	— 1
	Kaliánpúr . . . . .	+ 24 7'2	+ 77 39'4	538	978'723	0	978'888	978'825	978'867	— 42	+ 21
	Pahágarh . . . . .	+ 24 56'1	+ 77 41'8	500	978'740	0	978'893	978'835	978'923	— 88	— 30
	Usira . . . . .	+ 26 57'1	+ 77 37'9	247	978'972	+ 3	979'048	979'021	979'067	— 46	— 19
	Datairi . . . . .	+ 28 44'1	+ 77 39'0	218	979'095	0	979'162	979'137	979'200	— 63	— 38
	Kaliána . . . . .	+ 29 30'9	+ 77 39'2	247	979'107	0	979'183	979'154	979'260	— 106	— 77
Hima- layan.	Nojli . . . . .	+ 29 53'5	+ 77 40'5	269	979'116	0	979'198	979'167	979'290	— 123	— 92
	Meean Meer . . . . .	+ 31 31'6	+ 74 23'3	215	979'273	0	979'339	979'314	979'420	— 106	— 81
	Dehra Dún Observatory . . . . .	+ 30 19'5	+ 78 3'3	683	978'962	+ 7	979'172	979'100	979'324	— 224	— 152
	Mussooree . . . . .	+ 30 27'7	+ 78 4'4	2109	978'751	+ 27	979'400	979'181	979'335	— 154	+ 65
	Moré . . . . .	+ 33 15'7	+ 77 52'0	4696	978'137	+ 9	979'580	979'044	979'562	— 518	+ 18

#### EXPLANATION OF SYMBOLS EMPLOYED.

For fuller details as to the manner in which these numbers are derived, see the explanation of Table II.

$g \left(1 + \frac{2H}{R}\right)$  represents  $g \left(\frac{H+R}{R}\right)^2$ ; the third place of decimals in expressions for gravity at high stations may differ by two or three units according to the form of the formula used.

$g$  = the value of the force of gravity as observed at the height  $H$ , the value at Kew being assumed 981'200.

$g'$  = the observed value of gravity reduced to an infinite horizontal plain of height  $H$ .

$g' - g$  = topographical correction due to the irregular distribution of mass in the vicinity of the station.

$g_0$  = the observed value of gravity reduced to sea-level for height only.

$g_0'$  = the observed value of gravity reduced to sea-level both for height and for mass above sea-level.

$\gamma_0$  = the theoretical value of gravity computed from HELMERT'S formula of 1884, namely,  $978'000 \sin^2 \phi$ .

$g_0'' - \gamma_0$  = local variation of gravity from the normal, as computed by BOUGUER, and as used for the determination of mountain-compensation.

$g_0 - \gamma_0$  = local variation of gravity, as used by HELMERT in his determination of the Figure of the Earth.

The differences between the observed and computed values in Table I. correspond very nearly to the differences between the observed and computed values of  $N$ , as formerly given by General WALKER. That the correspondence is not exact is due to the adoption by HELMERT and WALKER of different constants in CLAIRAUT's law.

The physical meaning of BASEVI's pendulum results was for many years the subject of controversy.\* The deficiency of gravity which he had found to exist in Himalayan regions was attributed by some authorities to the elevation of the level surface above the surface of the mean spheroid, and by others to the defective density of the underlying crust; by the former the surface of the geoid was held to depart largely in certain places from that of the spheroid, and by the latter the two surfaces were assumed to be almost identical. In his 'Schwerkraft im Hochgebirge,' published in 1890, Professor HELMERT gave a mathematical solution of the problem, and his writings have closed the controversy.

A graphical interpretation of the results of Table I. is given in Plate 14, the method by which the several ordinates are computed being explained in Table II. below. The first figure of the Plate shows the height above sea-level, as determined by spirit levelling, of the surface of India along its central meridian. The second figure shows the deficiency of matter in the underlying crust, as deduced from BASEVI's pendulum results. The third figure gives the differences between the ordinates in the two upper figures, and shows the surface of India as it would be if the crust were everywhere of equal density. An examination of the figures of this Plate brings to light four significant facts:—

- (1) That there exists in the earth's crust throughout India a general deficiency of matter as compared to Europe;†
- (2) That the apparent excess of matter above sea-level, which the eye observes at Moré (Station 43) under the form of mountains, is largely compensated by subjacent deficiencies;
- (3) That an extraordinary deficiency of matter underlies the stations of Dehra Dun, Kaliaana and Nojli (Nos. 38, 37, 36), stations situated not in the Himalayas, like Mussooree (No. 41), but in the plains at the foot of the Himalayas; this deficiency leads one to believe that the pressure of the Himalaya Mountains upon the crust is diminishing the density of the latter under the surrounding plains;
- (4) If we disregard the evidence of fig. 1, and if we consider only the distribution of mass in the surrounding crust, we see that stations in the plains of

\* See preface to Vol. V. of 'Account of Operations of the Great Trigonometrical Survey of India.'

† The peninsula of India is composed of crystalline and volcanic rocks; the great age of the former and the great weight of the latter would lead us to expect a high value for  $g$ ; that  $g$  should be abnormally small is, from a geological point of view, surprising.

Northern India, such as Nos. 36 and 37, are situated in a deep wide valley between two ranges of mountains, one of which, the Himalayan, is visible, the other, with its summit at Station 24, invisible.\*

The northern end of the section in fig. 3 conveys the idea that the Himalayan mass is pressing upon the crust and producing a dimple, such as that described in Chapter VII. of Professor GEORGE DARWIN's work on 'Tides and Kindred Phenomena.'

The sections given in figs. 2 and 3 of Plate 14 are based on Professor HELMERT's condensation theory and have been constructed by means of his formulæ from the data in Table II. The numbers of the stations are not continuous, because pendulum observations were not taken at all the astronomical stations.

After 1874 no pendulum observations were taken in India, but the deflection of the plumb-line continued to be determined in different parts of the country. By the year 1900 the astronomical latitude of 159 stations, the astronomical azimuth at 209, and the amplitude of 55 arcs of longitude had been observed, and thus a large amount of evidence relating to the *direction* of gravity had accumulated. A discussion of the data† then available showed that it would be desirable to associate determinations of the *intensity* of the force of gravity with observations of the plumb-line, and in 1902 the Indian Government sanctioned the re-opening of pendulum observations and the purchase of a new apparatus of VON STERNECK's pattern.

## (2.) *The Pendulum Observations of 1903-04.*

The new apparatus was standardised at Kew and Greenwich in the autumn of 1903, and was taken to India by Major LENOX CONYNGHAM in November of that year. Upon its arrival he thought it advisable to commence work at some of BASEVI's stations. The accuracy of BASEVI's results, as given in Tables I. and II., had been questioned by Professor HELMERT in his report to the International Geodetic Conference of 1900. It had been there pointed out that the observer had had no means of measuring the flexure of the pendulum stand, that during his standardisation at Kew his pendulums had not been supported on the stand subsequently used in India but between a stone pillar and a wall, and that when he visited the high Himalayan station of Moré he had substituted a light portable stand for that belonging to the Royal Society's apparatus.

\* Fig. 1 of Plate 14 shows that the altitude of Station 38 above sea-level is 145 metres greater than that of Station 24; fig. 3 shows that if the underlying crust were brought to a uniform density of 2·8 the altitude of Station 38 would be 1430 metres less than that of Station 24. The visible fall of nearly 500 feet from Station 38 to Station 24 is converted by the pendulum diagrams into a rise of nearly 4700 feet.

† 'Professional Papers of the Survey of India,' No. 5 of 1902. "The Attraction of the Himalaya Mountains upon the Plumb-line in India."

TABLE II.

Number on Sections on Plate I.	Station.	Latitude.	Distance from Punnae to scale 8 millims. = 1° latitude.	H = Height above sea-level.	Height in fig. 1 1 centim. = 1250 metres.	$g'' - \gamma_0$ from Table I.	$D = - (g'' - \gamma_0) \times 8.6573$ metres.	Depth in fig. 2 1 centim. = 1250 metres.	H - D.	
			Millims.	Metres.	H to scale in millims.		Metres.	D to scale in millims.	Metres.	To scale in millims. for fig. 3.
1	Punnae. . . . .	8 9.5	0	15	0.1	- 7	+ 61	+ 0.5	- 46	- 0.4
2	Kudankolam. . . .	8 10.4	1	51	0.4	- 5	+ 43	+ 0.3	+ 8	+ 0.1
4	Mallapatti. . . .	9 29.0	106	88	0.7	- 33	+ 286	+ 2.3	- 198	- 1.6
5	Pachapallam. . . .	10 59.7	227	296	2.4	- 49	+ 424	+ 3.4	- 128	- 1.0
6	Bangalore, South. .	13 0.7	388	950	7.6	- 84	+ 727	+ 5.8	+ 223	+ 1.8
7	Bangalore, North. .	13 4.9	394	917	7.3	- 73	+ 632	+ 5.1	+ 285	+ 2.2
10	Namthabád. . . .	15 5.9	555	353	2.9	- 77	+ 667	+ 5.3	- 309	- 2.4
12	Kodangal. . . . .	17 8.0	718	584	4.7	- 57	+ 493	+ 3.9	+ 91	+ 0.8
13	Damargida. . . .	18 3.3	791	593	4.8	- 103	+ 892	+ 7.1	- 299	- 2.3
15	Somtana. . . . .	19 5.0	874	522	4.2	- 53	+ 459	+ 3.7	+ 63	+ 0.5
17	Badgaon. . . . .	20 44.4	1006	342	2.7	- 48	+ 416	+ 3.3	- 74	- 0.6
20	Ahmadpúr. . . . .	23 36.4	1235	516	4.1	- 59	+ 511	+ 4.0	+ 5	+ 0.1
24	Kaliánpúr. . . . .	24 7.2	1276	538	4.3	- 42	+ 364	+ 2.9	+ 174	+ 1.4
29	Pahárgarh. . . . .	24 56.1	1342	500	4.0	- 88	+ 762	+ 6.1	- 262	- 2.1
31	Usira. . . . .	26 57.1	1503	247	2.0	- 46	+ 398	+ 3.2	- 151	- 1.2
35	Datáiri. . . . .	28 44.1	1646	218	1.8	- 63	+ 545	+ 4.4	- 327	- 2.6
36	Kalána. . . . .	29 30.9	1709	247	2.0	- 106	+ 918	+ 7.3	- 671	- 5.3
37	Nojli. . . . .	29 53.5	1733	269	2.1	- 123	+ 1065	+ 8.5	- 796	- 6.4
38	Dehra Dún. . . . .	30 19.5	1774	683	5.5	- 224	+ 1939	+ 15.5	- 1256	- 10.0
41	Mussooree. . . . .	30 27.7	1783	2109	16.9	- 154	+ 1333	+ 10.7	+ 876	+ 6.2
43	Moré. . . . .	33 15.7	2008	4696	37.6	- 518	+ 4484	+ 35.9	+ 212	+ 1.7

## EXPLANATION OF TABLE II.

Given the amount of matter in the crust at a standard station, we wish to find from pendulum observations the excess or deficiency of matter underlying any other station; from observation we find  $dg$ , the local variation of gravity from the normal, and we wish to determine the mass whose attraction at sea-level is equivalent to  $dg$ . From its attraction only we cannot determine both the height and density of a hidden mass, but if we assume that the density is equal to 2.8, the normal density of surface rocks, we can then ascertain the height; by this assumption we mean that the density of a hidden disturbing mass is 2.8 in excess of the normal density of the surrounding crust. The problem to be solved is, therefore: given a small attraction  $dg$ , what is the height of the attracting mass, its density being 2.8?

It is necessary to consider how  $dg$  is obtained; by observations taken at a station of height  $H$  we find the value of gravity to be  $g$ . To obtain the corresponding value of gravity at sea-level,  $g_0$ , we have firstly to correct for the amount  $H$ , by which the distance of the station from the centre of the earth exceeds the earth's radius,  $\frac{g_0}{g} = \frac{(R+H)^2}{R^2}$ ;  $g_0 = g \left(1 + \frac{2H}{R}\right)$ .

This correction would be sufficient if the observing station were in mid-air and over the ocean, but when we observe at a station on land, we have to consider the attraction of that portion of the crust that lies between sea-level and the station; this attraction tends to increase the observed value of  $g$ , and the correction for it is negative. The attraction of a horizontal plateau of height  $H$  and density  $\delta$  upon a pendulum situated at the centre of its upper surface is  $A = 2\pi\delta H$ . The force of gravity at sea-level is  $g = \frac{4}{3}\pi R\Delta$ , where  $\Delta$  is the mean density of the earth.  $\frac{A}{g} = \frac{2\pi\delta H}{\frac{4}{3}\pi R\Delta} = \frac{3}{2} \cdot \frac{\delta}{\Delta} \cdot \frac{H}{R}$ ; assuming  $\delta = 2.8$  and  $\Delta = 5.6$ ,  $A = \frac{3}{4} \cdot \frac{H}{R}g$ .

Then if  $g_0''$  be the value of gravity at sea-level corrected both for height of station and for the attraction of the intervening mass, we get the well-known formula of BOUGUER,  $g_0'' = g_0 - A = g \left(1 + \frac{2H}{R} - \frac{3H}{4R}\right)$ .  $g_0''$  gives then the observed value of gravity at an ideal station, situated upon a continent, whose surface is level with the sea.

Now  $dg = g_0'' - \gamma_0$ , where  $\gamma_0$  is the theoretical value of gravity. To find the height of a plateau whose attraction would be sufficient to increase the observed force of gravity by 0.001 centim., we have  $\frac{3}{4} \cdot \frac{H}{R} \cdot g = dg = 0.001$ .  $H = 0.001 \times \frac{4}{3} \times \frac{R}{g}$ . Assuming the earth to be a sphere with a mean radius of 6367000 metres, and the mean value of the force of gravity to be 980.6, we get  $H = 0.001 \times \frac{4}{3} \times \frac{6367000}{980.6} = 8.6573$  metres.

The attraction thus of a plateau of height 8.6573 metres will increase the observed value of gravity by 0.001, and *vice versa*; if the observed value of gravity at sea-level differs from the theoretical value by +0.001 there is an excess of matter in the underlying crust equal to a disc 8.6573 metres thick of a density 2.8.

If we imagine that from the surface to a depth  $D$ , the density of the crust underlying the station is less by 2.8 than the normal surface density, then  $D = - (g_0'' - \gamma_0) 8.6573$  metres. The visible excess of matter will be equal to  $H$  (see fig. 1), the hidden deficiency will be equal to  $D$  (see fig. 2), and the actual disturbing mass, shown in the section of fig. 3, will be  $(H - D)$ .

From Table II, it appears that at Moré the value of  $g_0''$  is 0.518 less than  $\gamma_0$ ; therefore the hidden deficiency =  $D = 518 \times 8.6573 = 4484$  metres (fig. 2). The height of the visible mountain at Moré is  $H = 4696$  (fig. 1); the actual excess of matter in the crust at Moré =  $(H - D) = 212$  metres (fig. 3).

At Dehra Dún ( $g_0'' - \gamma_0 = -0.224$ , hidden deficiency =  $D = 224 \times 8.6573 = 1939$  metres (fig. 2). The altitude of Dehra Dún is 683 metres (fig. 1); at this station, then, the hidden deficiency exceeds the visible excess, and the resultant is  $(H - D) = 683 - 1939 = -1256$  metres (fig. 3).

At the important station of Kaliánpur ( $g_0'' - \gamma_0 = -0.042$ , the hidden deficiency =  $D = 42 \times 8.6573 = 364$  metres, the visible excess at Kaliánpur =  $H = 538$  metres. There exists, therefore, at Kaliánpur a resultant excess of matter in the crust equal to a disc of density 2.8, and of height 174 metres. The existence of this excess has been questioned, and the calculation is therefore given in detail,

From the results of observations taken by Austrian observers at some of the coast stations, Professor HELMERT had arrived at the conclusion that BASEVI's values required a correction of  $+0.047$ .<sup>\*</sup> The importance of such a correction cannot be overestimated; it would have indeed the effect of largely neutralising the negative character of the values of  $(g_0'' - \gamma_0)$  and of  $(H - D)$  in Tables I. and II., and it would render the value of  $(g_0'' - \gamma_0)$  for our standard station of Kaliánpur actually positive. Such a correction would lower the line of sea-level as drawn on figs. 2 and 3 of Plate 14, but would not otherwise affect the sections in these figures.

Major LENOX CONYNGHAM's first station in India was Dehra Dún; his results there were astonishing, for they showed that BASEVI's value was no less than 0.103 centim. too small.<sup>†</sup> LENOX CONYNGHAM then visited Calcutta, Bombay, Madras, and Mussooree. At Calcutta observations were rendered impossible by the ceaseless vibrations of the ground, which proved sufficient to cause the pendulums, if left suspended at rest, to oscillate visibly in a few minutes; this effect on the pendulums was produced in whatever plane the latter were swung. LENOX CONYNGHAM had therefore to abandon Calcutta without obtaining any results; that he failed where BASEVI had succeeded was probably due to the half-seconds pendulums of the new apparatus being more affected by earth-vibrations than the old seconds pendulums.

<sup>\*</sup> The correction for Moré was indeterminate, but probably larger than 0.047, owing to the lightness of the stand employed.

<sup>†</sup> This extraordinary difference could only mean that BASEVI's final value of  $N$  was too small by 4 whole seconds of time. BASEVI's observations at Dehra Dún lasted four months, and included 234 independent sets of swings taken at pressures varying from half-an-inch to 28 inches, and at temperatures varying from  $48^\circ$  to  $102^\circ$  Fahrenheit.

	N.	$g$ .
BASEVI's 1st determination . . . . .	seconds 86,021.38	centims. 978.973
" 2nd " . . . . .	86,020.74	978.959
Weighted mean . . . . .	86,020.86	978.962
LENOX CONYNGHAM in January, 1904 . . . . .		979.063
" " June, 1904 . . . . .		979.066
Mean . . . . .		979.065
Difference between BASEVI's two determinations = 0.014 centim.		
" " LENOX CONYNGHAM's two determinations = 0.003 centim.		
" " BASEVI and LENOX CONYNGHAM = 0.103 centim.		

## THE Force of Gravity in Dynes as observed by—

	BASEVI and HEAVISIDE in 1866-73.	LENOX CONYNGHAM in 1904.	Difference.
	centims.	centims.	centims.
Dehra Dún . . . . .	978·962	979·065	+ 0·103
Madras . . . . .	978·237	978·281	+ 0·044
Bombay . . . . .	978·605	978·632	+ 0·027
Mussooree . . . . .	978·751	978·795	+ 0·044

LENOX CONYNGHAM'S observations confirm Professor HELMERT'S prediction that BASEVI and HEAVISIDE'S results would be found too small. The sections in figs. 2 and 3 of Plate 14 of this paper have been based on their results, and it may be asked what purpose has been served by the construction of sections from impugned data? The answer to this question is that BASEVI'S results have been accepted by geodesists and have formed the basis of controversies and theories; they have, too, been rendered historic by the difficulties and death of the observer at Moré, and by the great light they undoubtedly threw upon Himalayan formation. Now that pendulum observations are being re-opened, I have thought it advisable in an historical retrospect to give a graphical summary of the results that were formerly obtained, and that have so profoundly influenced the ideas of geodesists.

In figs. 2 and 3 the deficiency underlying Dehra Dún (38) will be reduced by almost one-half if LENOX CONYNGHAM'S value be substituted for BASEVI'S. Similarly the height of Mussooree (41) in fig. 3 will be almost doubled.

In the near future BASEVI'S other stations will possibly be visited; it seems certain that his results will everywhere be found too small, that throughout fig. 2 the curve of deficiency will have to be raised, and that in fig. 3 the line of sea-level will have to be lowered.

From LENOX CONYNGHAM'S observations at Bombay and Dehra Dún, it appears that BASEVI'S and HEAVISIDE'S results are not in error by any constant quantity, and that the error of each will have to be separately determined; it is not easy to account for the variation in the magnitudes of their errors; their observations were taken with a care that it is difficult for us to equal; in assuming that flexure could be prevented by the employment of a rigid stand, the old observers were following the highest authorities of their time; the only faults that have been found with their work are such as would tend to produce constant error. That their errors vary so largely can only, I think, be explained on the supposition that the flexure of the wooden stand of the Royal Society's apparatus was influenced by temperature and humidity.

The idea that gravity is exceptionally weak throughout India as compared to

Europe can no longer be upheld;\* the so-called “marked negative variation” of many writers has been found to rest on erroneous data.

The theory of the compensation of the Himalayas has been based to a large extent on the old pendulum results at Mussooree and Moré. The sections in figs. 2 and 3 show that a hidden deficiency of matter underlies the station of Mussooree (41) equivalent to about three-fifths of the visible excess; LENOX CONYNGHAM's recent result reduces this hidden deficiency to one-third only of the visible excess.

Figs. 2 and 3 might lead to the belief that the Himalayas at Moré (43) are almost *entirely* compensated. The height of the visible excess is 4696 metres, the depth of the ideal deficiency 4484 metres. But LENOX CONYNGHAM has not visited Moré, and, as BASEVI employed there a special and lighter stand, it is impossible to gauge the error introduced into his result by its flexure; we have lately gained some idea of the effects of the flexure of the Royal Society's heavy stand, and we can only suppose that the light Moré stand was less rigid. That the Himalayas at Moré are compensated to a considerable extent is certain; that the error due to flexure could have affected BASEVI's result to the extent of 22 seconds of time is out of the question. On the other hand, it is more than probable that the compensation, that does exist, lacks that completeness, which has hitherto been considered among its most remarkable features.†

### (3.) *Deflections of the Plumb-line.*

In 1895 General WALKER published an admirable classification of the deflections of the plumb-line that had been observed in India.‡ His object was to present the data in the form of arcs of meridian and parallel for the use of mathematicians investigating the values of the earth's axes.

In 1898 Great Britain joined the International Geodetic Association, and Professor GEORGE DARWIN, F.R.S., was nominated to represent her at International Conferences. These steps have brought India into touch with modern European ideas, and have shown us that the aims of geodesy are no longer limited to the measurements of arcs of meridian and parallel, and to the determinations of the axes of a mean spheroid. At the International Conference, held at Copenhagen in 1903, the following resolution was passed :—

“ Il est désirable qu'on fasse dans les Indes anglaises une étude approfondie de la répartition de la pesanteur, tant dans les contrées montagneuses que dans les plaines.

\* No standard value of  $g$  has as yet been adopted by the International Geodetic Association. When the absolute values of gravity at European standard stations have been finally determined, it may be found that the values at Kew and Greenwich, which we are now accepting as our standards, are not themselves normal. Both BASEVI's old and LENOX CONYNGHAM's new values will then have to be corrected by a constant quantity.

† CLARKE'S 'Geodesy,' p. 350.

‡ 'Phil. Trans.,' A, vol. 186, 1895.

“Attendu que c’est seulement par cette étude qu’on pourra obtenir une représentation exacte de la distribution des masses dans l’écorce terrestre et de la forme du géoïde dans ces contrées.”

In India itself our view of the subject has been modified by our recent discoveries that the direction of gravity is liable to a constant deflection throughout large regions, and that the density of the earth’s crust may differ constantly from the mean surface value throughout great areas. In 1895, when General WALKER’S paper was written, it was believed that deflections of the plumb-line were accidental and due to small local pockets of exceptional density studding every part of the country. It was considered proper to treat deflections by minimum squares,\* and it was held that the true direction of the normal to the mean figure could be discovered by grouping stations round a centre, and by assuming that in the mean of the group the effects of local attraction are cancelled.

There are now grounds for believing that the direction of gravity may be deflected through 8 seconds of arc or more over an area of thousands of square miles. To assume, therefore, that its mean direction as deduced from a group of contiguous stations coincides with the normal, is seen to be hardly more justifiable than to assume that the mean direction of the magnetic needle, as observed at several stations in Surrey, gives the true direction of north.

The investigation of the laws governing the deflection of gravity in India has been impeded by many difficulties. Political considerations have erected a barrier round Nepal and Bhutan, which geodetic operations have been unable to pass. Nepal and Bhutan include almost the whole of the central and southern Himalayas. Geodesists wish to approach the Himalayas from the south, and, by working gradually towards their centre of mass, to discover their influence on the plumb-line. Being excluded from Nepal and Bhutan, they have had to attack the mountainous area at its south-west salient at Dehra Dún (see Plate 16).

They have, moreover, been generally confined to deducing the direction of gravity from latitude observations, which give only the meridional component. It is true that our longitude observations show the direction of gravity in the prime vertical, and if we could observe both the latitude and longitude of points on the Himalayan snows, it would be possible to calculate the actual direction of gravity from its two measured components. But until wireless telegraphy can be utilised for longitude determinations, our longitude stations will have to be located near telegraph offices instead of on mountain tops. We have observed astronomical azimuths at numerous stations and their results will in the future be available for plumb-line discussions, but

\* When arcs of meridian are employed to determine the figure of the mean spheroid they are not regarded as fixed in latitude. Their most probable positions in latitude are found by the method of minimum squares. Each arc is moved up or down its meridional ellipse until a position is found for it in which the squares of the deflections of the plumb-line are a minimum; by this method large deflections may be eliminated that exist in nature.

the geodetic azimuths are at present affected by the errors accumulated in the triangulation, which have not as yet been determined. Whilst, then, we are endeavouring to discover the influence on the plumb-line of a mountainous mass situated to the north-east, we are limited to observations which give the north and south component only.

The other difficulties attending plumb-line research are, that our deductions are based upon an assumed figure of the earth and upon an assumed direction of gravity at a station of origin. We have to imagine a mean spheroid, and we then assume that the angle of inclination between the surface of this spheroid and the actual level surface at any place is equal to the deflection of the plumb-line; we have also to select some station as an origin, and to assume that the surfaces of the spheroid and geoid are there parallel. We have finally to decide from the results accumulated over wide areas, whether the fundamental assumptions on which those results are based—the assumptions of spheroid and origin—are correct.

In the publications of the 'Survey of India' the deflections of the plumb-line have been always based (1) on the mean spheroid of EVEREST, and (2) on the assumption that gravity acts normally at Kaliánpur, our geodetic origin. In his paper on 'Geodesy,' published in 1895, General WALKER gave the deflections of the plumb-line in terms of the spheroid of CLARKE.

EVEREST's spheroid had agreed closely with BESSEL's; but the objection had been raised to both that their values of the ellipticity,  $1/300\cdot80$  and  $1/299\cdot15$ , differed too seriously from the value  $1/289$  derived by CLAIRAUT's theorem from pendulum observations. In 1880, in his work on 'Geodesy,' Colonel CLARKE deduced an ellipticity of  $1/293\cdot465$  from measures of arcs, and of  $1/293$  from pendulum results; and his removal of the hiatus gave great weight to his spheroid. Professor HELMERT's investigations have, however, shown that modern pendulum work has not borne out CLARKE's result, and that BESSEL's ellipticity was after all nearer the truth.

Recent geodetic measurements have tended to confirm the accuracy of CLARKE's value of the major axis, and to indicate that BESSEL's value was too small.\* Until a new determination of the dimensions of the mean spheroid has been made under the authority of the International Geodetic Association, it is advisable for us to adopt for computations a spheroid *that has the major axis of CLARKE and the ellipticity of BESSEL.*

#### ELEMENTS of Spheroids.

	Major axis in metres.	Ellipticity.
BESSEL . . . . .	6,377,397	$1/299\cdot15$
EVEREST . . . . .	6,377,193	$1/300\cdot80$
CLARKE . . . . .	6,378,190	$1/293\cdot47$
CLARKE-BESSEL . . . . .	6,378,190	$1/299\cdot15$

\* 'United States Coast and Geodetic Survey.' "The Transcontinental Triangulation, 1900 ;" "The Eastern Oblique Arc of the United States," 1901.

In Tables III. and IV., given hereafter, the deflections are shown in terms of the Everest, the Clarke, and the Clarke-Bessel spheroids.

If we compare the deflections of the plumb-line as referred respectively to the Everest and Clarke spheroids, we find that the values are almost identical at all stations. The agreement between the two series, though very remarkable, is a mere coincidence; the influence of CLARKE'S increased ellipticity happens always in India to neutralise the influence of his increased major axis.

If we employ the Clarke-Bessel spheroid, the deduced deflections of gravity are appreciably modified.

#### (4.) *The Regional Classification of Deflections.*

It was in 1900 that the suggestion was first made that the deflections of gravity in India, which had hitherto been attributed to accidental and local attractions, could be broadly classified by regions. This new theory had as a working hypothesis an advantage over the old in that it could be tested by further investigation in the field. From the classification of results of regions it was predicted that a southerly deflection of gravity would be found to exist throughout a great zone enclosing the main valley of the Ganges and running parallel to the Himalayas for 1000 miles; but that both north and south of this zone northerly deflections would be met with (*vide* Plate 15).

With the object of testing the correctness of these predictions, Lieutenant COWIE, R.E., proceeded in 1901 to observe several latitudes between Calcutta and Phallut, working across the zone of southerly deflection and up to the Himalayas (*vide* Plate 15). The results which he obtained were as follows:—In the country immediately south of the zone northerly deflections of 3" and 4" were found; at Calcutta the inclination of gravity was slightly southerly. In the 200 miles immediately north of Calcutta, COWIE found southerly deflections at four successive stations; the inclination of gravity then changed to northerly, at Jalpaiguri it was 6" northerly, at Siliguri 23", at Kurseong 51", and at Phallut 37".

In 1902–03, Lieutenant COWIE was directed to work again northwards across the zone and to follow the meridian of 79°. The results which he obtained were as follows:—In latitude 23° 30' the direction of gravity was inclined 5" towards the north; in the next 200 miles Lieutenant COWIE found a southerly deflection at seven successive stations; in latitude 27° 47' the inclination of gravity began to be slightly northerly; in 29° 16' its inclination was 12" northwards. At Birond, in the hills, Lieutenant COWIE found a deflection of 44" north.

It can, therefore, now be prophesied with tolerable certainty that on all Himalayan meridians the direction of gravity will be found to follow one general law; in the neighbourhood of the tropic, as we move northwards, its direction will change from northerly to southerly; it will then remain deflected towards the south for some

hundreds of miles, and it will again become northerly as the Himalayas come into view.

In spite, therefore, of the fact that the true direction of gravity at any one place cannot be determined with certainty, yet it is possible now to classify deflections of the plumb-line in India by regions. A modification of the spheroid of reference may alter values and may move the regional boundaries, but it will not affect the general correctness of the classification. A change in the assumed value of the direction of gravity at the station of origin will alter all deduced deflections of the plumb-line by the same amount, but it will not affect their differences, nor the mean differences between regions.

I propose now to show :

- (1) The classification of stations by regions.
- (2) The effects on the classification of changes in the spheroid of reference.
- (3) The effects on the classification of the existence of a deflection at the origin.
- (4) The final values of deflections of gravity, corrected for errors of spheroid and origin.

In Plate 15 India has been divided into four regions :

- (1) The Himalayas, (2) the zone of southerly deflections, (3) the Indian Peninsula, (4) North-west India.

In the following four Tables IIIA., IIIB., IIIC., IIID., which correspond to the four regions, the direction of gravity at Kaliánpur has been assumed to be coincident with the normal to the spheroid, and has been adopted as the datum. The deflections of gravity are given in the columns headed (A—G); the symbol A denotes the astronomical or observed value of latitude, G denotes the geodetic value of latitude, which has been calculated through the triangulation extended from the origin over the spheroid.

TABLE IIIA.\*—Sub-Himalayan Region. Deflections of the plumb-line in the meridian as observed at stations in the sub-Himalayan region. Of the 42 stations included in this Table, 19 are situated in the mountains and 23 in the plains at the foot of the mountains. See Plate 16.

Latitude.	Meridian of 75°.			Meridian of 77° 30'.			Meridian of 78° 30'.			Meridian of 80°.			Meridian of 86°.			Meridian of 88°.		
	Name of station.	Distance from Himalayan boundary.	A—G. Everest spheroid. Clarke spheroid.	Name of station.	Distance from Himalayan boundary.	A—G. Everest spheroid. Clarke spheroid.	Name of station.	Distance from Himalayan boundary.	A—G. Everest spheroid. Clarke spheroid.	Name of station.	Distance from Himalayan boundary.	A—G. Everest spheroid. Clarke spheroid.	Name of station.	Distance from Himalayan boundary.	A—G. Everest spheroid. Clarke spheroid.	Name of station.	Distance from Himalayan boundary.	A—G. Everest spheroid. Clarke spheroid.
34°	Murree .	— 20	— 20 — 18	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"
	Ranjitgarh	+ 16	— 5 — 4															
32°	Sháhpur .	38	+ 1 + 2															
	Amritsar .	65	+ 4 + 5															
31°	Sangatpur	75	+ 1 + 2	Lambatach	— 46 — 34 — 33		Kidarkanta	— 50 — 30 — 29										
	Isanpur .	130	— 4 — 3	Bajamara	— 28 — 28 — 27		Balak .	— 31 — 27 — 26										
				Banog .	— 7 — 33 — 32													
				Mussoorree	— 4 — 37 — 36													
				Ráipur .	0 — 47 — 47													
				Ámsot .	+ 8 — 29 — 28													
				Dehra Dún (old) .	6 — 37 — 36													
				Dehra Dún (new) .	6 — 37 — 36													
30°				Dehra Dún Base-line E. End .	7 — 30 — 29													
				Nojli .	40 — 13 — 13													
				Kaliána .	60 — 7 — 6		Sarkára .	+ 50 — 12 — 11		Birond .	— 10 — 44 — 43							
29°				Datairi .	110 — 6 — 5		Sirsa .	— 9 — 8										
				Bostán .	125 — 5 — 5		Bánsghópál .	101 — 5 — 4		Ránuápur .	+ 55 — 11 — 10							
				Chandaos .	155 — 1 — 0		Sankráo .	138 0 + 1										
28°				Noh .	170 0 + 1		Salimpur .	158 0 + 1		Jarúra .	80 — 6 — 5		Kaulia .	— 42 — 33 — 32				
													Mahadeo Pokra .	— 36 — 38 — 37				
27°				Agra .	220 — 5 — 5					Nimkár .	125 0 + 1		Phallut .	— 40 — 37 — 37				
													Tongla .	— 25 — 42 — 42				
													Senchal .	— 20 — 36 — 35				
													Kurseong .	— 10 — 51 — 50				
				Usra .	253 — 6 — 5								Siliguri .	+ 5 — 23 — 22				
26°													Jalpáiguri .	+ 28 — 6 — 5				

\* The negative sign denotes a southerly deflection, the positive a southerly. N. B.—In the column headed "Distance from Himalayan Boundary," the negative sign opposite a station denotes that the station is situated within the Himalayas. The latitude of Kaliapur has been taken  $24^{\circ} 7' 10''$ .97.

TABLE IIIb.—The Zone of Southerly Deflection. Deflections of the plumb-line in the meridian as observed at stations in the zone of southerly deflection, the direction of gravity being assumed to be normal at Kaliánpur.

Latitude.	Meridian of 73°.			Meridian of 75°.			Meridian of 77° 30'.			Meridian of 78° 30'.			Meridian of 80°.			Meridian of 82°.			Meridian of 84°.			Meridian of 86°.			Meridian of 88°.			Latitude.
	Name of station.	Everest spheroid.	A-G.	Name of station.	Everest spheroid.	A-G.	Name of station.	Everest spheroid.	A-G.	Name of station.	Everest spheroid.	A-G.	Name of station.	Everest spheroid.	A-G.	Name of station.	Everest spheroid.	A-G.	Name of station.	Everest spheroid.	A-G.	Name of station.	Everest spheroid.	A-G.	Name of station.	Everest spheroid.	A-G.	
29	Telu . . +1 +2	"	"		"	"		"	"		"	"		"	"		"	"		"	"		"	"		"	"	29
28	Khirsar . +3 +4																											28
27	Bithnok . +3 +4																											27
	Jambo . . +3 +4																											26
	Chamu . +1 +1																											25
				Rewat . . +1 +1																								24
				Jetgarh . +2 +2																								23
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																												5
																												4
																												3
																												2
																												1
																												0

The latitude of Kaliánpur has been taken  $24^{\circ} 7' 10''$  '97.





TABLE III.

Summary of the four preceding tables.

Region.	Number of stations.	Mean deflection of the plumb-line.			
		Everest spheroid.		Clarke spheroid.	
Sub-Himalayan { mountains . . .	19	"	"	"	"
		- 35	± 1.15	- 34	± 1.19
plains . . . . .	23	- 5	± 0.82	- 4	± 0.83
Zone of southerly deflection. . .	43	+ 3	± 0.24	+ 3	± 0.24
Indian peninsula . . . . .	85	- 3	± 0.28	- 4	± 0.28
North-west India . . . . .	27	- 1	± 0.23	- 1	± 0.23

It will be seen that in the Himalayas the deflections are northerly and large, but that as we move southwards from the mountains they decrease rapidly—more rapidly in fact than the law of gravitation requires.

As we recede still further from the Himalayas we enter the positive zone, and here we find a region 1000 miles long and 200 broad running parallel to the Himalayas, throughout which the plumb-line is always deflected towards the south.

As we progress still further southwards we enter the Indian peninsula; on crossing the boundary line between the 2nd and 3rd regions we find that the deflection of the plumb-line changes its direction and sign; between latitudes  $24^{\circ}$  and  $18^{\circ}$ , from coast to coast, strong northerly deflections averaging  $6''$  now prevail; as we move southwards towards Cape Comorin these northerly deflections slowly decrease, and in the extreme south of India change to southerly.

In North-western India the latitude observations have not brought to light any marked characteristic. This region is west of the Himalayas, and longitude determinations, if made at numerous stations, would be more likely than latitude observations to yield instructive results.

The opinion had been expressed that the large deflections of  $30''$  and  $40''$ , discovered in the sub-Himalayas near Mussooree and Phallut, might prove to be local and exceptional, and that it was unsafe to assume them characteristic of the region. To test the correctness of this view, Captain COWIE observed for latitude in April, 1903, at the Himalayan Station of Birond, and found that the direction of gravity was deflected here  $44''$  towards the north; in November, 1903, Captain H. WOOD, R.E., observed for latitude at two stations in Central Nepal and met with deflections of  $33''$  and  $38''$ . All the evidence that is slowly accumulating tends, therefore, to show

that these large deflections of gravity are not confined to exceptional localities, but prevail throughout a vast region.

In October, 1903, Captain COWIE was directed to extend the Great Arc of India northwards across the Mussooree hills to the snowy range, and to observe for latitude in the inner Himalayas. High authorities had expressed the opinion that the large deflections of gravity at Dehra Dún, Birond, and Phallut were due not to the Himalayan mass, but to the peculiar geological formation of its lower and outer range; that these deflections would be found to disappear when the first Himalayan ridges were crossed, and that large southerly deflections would be met with in the inner Himalayas. Captain COWIE extended the Great Arc of India into the mountains from latitude  $30^{\circ} 29'$  to  $31^{\circ} 1'$ , a distance of 35 miles, and he observed for latitude at the Himalayan stations of Bahak (9715 feet high), Bajamara (9681 feet), Lambatach (10,474 feet), and Kidarkanta (12,509 feet). Table IIIA. shows that large northerly deflections were met with at all these stations.

The form of the ideal section deduced in fig. 3, Plate 14, from pendulum results rather justified the belief that deflections would be found to decrease rapidly between Station 41 (Mussooree) and Station 43 (Moré). The northerly deflection of  $30''$  now discovered by COWIE at Kidarkanta\* consequently throws doubt on the correctness of that portion of the pendulum section that lies between these two stations, and confirms the opinion that a greater excess of matter exists at Moré than has been deduced from BASEVI's observations.

In Plate 17 is given a cross-section of the Himalayas, drawn by Captain COWIE, through the stations of Kidarkanta and Moré; this section is not ideal but real; it shows the variations in the actual level of the ground, and illustrates the visible mountain mass separating the two stations; the vertical scale is twenty times as great as the horizontal.

Plates 18, 19 and 20, drawn by Captain COWIE, give cross-sections of the Himalayas at Kidarkanta, Birond, and Phallut; they illustrate the increase in elevation between the plains of India and the plateau of Tibet at three different places. In each the vertical scale is ten times as great as the horizontal; the scales employed in these three last plates are larger than those used in Plate 17.

\* As an observer penetrates a mountain range, he leaves more and more of the mountainous mass behind him; the attraction of the portion left behind is then opposed to the attraction of the masses still confronting him, and tends to decrease the resultant deflection of his plumb-line. To determine the relative effects of the rearward and forward masses a contoured map is necessary.

(5.) *The Adoption of a New Spheroid.*

The deflections have so far been deduced from the Everest and Clarke spheroids only. It is now proposed to show the values that will be obtained if the Clarke-Bessel spheroid, as described above, be adopted.

In the Tables IVA., IVB., IVC., IVD., and IVE. is given the inclination at every station between the observed level surface and the surface of the Clarke-Bessel spheroid.

The inclinations are stated, firstly, when that at Kaliánpur is taken as zero, and, secondly, when it is taken as  $+6''$ . The reason for adopting this latter assumption will be explained in section (6) on the zero of verticality.

TABLE IV.A.—Sub-Himalayan Region.

Latitude.	Meridian of 75°.			Meridian of 77° 30'.			Meridian of 78° 30'.			Meridian of 80°.			Meridian of 82°.			Meridian of 83°.		
	Name of station.	Distance from Himalayan boundary.	A—G Clarke-Bessel spheroid.		Name of station.	Distance from Himalayan boundary.	A—G Clarke-Bessel spheroid.		Name of station.	Distance from Himalayan boundary.	A—G Clarke-Bessel spheroid.		Name of station.	Distance from Himalayan boundary.	A—G Clarke-Bessel spheroid.			
			Referred to Kaliānpur as zero.	Referred to Kaliānpur as +6".			Referred to Kaliānpur as zero.	Referred to Kaliānpur as +6".			Referred to Kaliānpur as zero.	Referred to Kaliānpur as +6".						
° 34	Murree .	— 20	— 16	— 10	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Ranjitgarh .	+ 16	— 2	+ 4	"	"	"	"	"	"	"	"	"	"	"	"	"	
32	Shāhpur .	38	+ 4	+ 10	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Amritsar .	65	+ 7	+ 13	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Sangatpur .	75	+ 4	+ 10	"	"	"	"	"	"	"	"	"	"	"	"	"	
31	Isanpur .	130	— 1	+ 5	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Lambatach .	— 46	— 31	— 25	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Bajamara .	— 28	— 25	— 19	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Banog . . .	— 7	— 30	— 24	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Mussooree .	— 4	— 34	— 28	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Rājpur . . .	0	— 45	— 39	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Ánsot . . .	+ 8	— 26	— 20	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Dehra Dún (old) . . .	6	— 35	— 29	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Dehra Dún (new) . . .	6	— 34	— 28	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Dehra Dún Base-line E. End .	7	— 28	— 21	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Nojli . . .	40	— 11	— 5	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Kaliāna . .	60	— 5	+ 2	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Datairi . .	110	— 4	+ 2	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Bostán . .	125	— 4	+ 3	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Chandaos .	155	+ 1	+ 7	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Noh . . .	170	+ 1	+ 8	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Agra . . .	220	— 4	+ 2	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Usira . . .	253	— 5	+ 2	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Phallut . .	— 40	— 36	— 30	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Tonglu . .	— 35	— 41	— 35	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Senchal . .	— 30	— 35	— 29	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Kurseong .	— 10	— 50	— 44	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Siliguri . .	+ 5	— 22	— 16	"	"	"	"	"	"	"	"	"	"	"	"	"	
	Jaipáiguri .	+ 28	— 5	+ 1	"	"	"	"	"	"	"	"	"	"	"	"	"	
26																		

N.B.—In the column headed "Distance from Himalayan boundary," the negative sign opposite a station denotes that the station is situated within the Himalayas.

TABLE IVB.—The Zone of Southerly Deflection.

[illegible]





TABLE IV<sub>E</sub>.

Summary of the four preceding tables.

Region.	Number of stations.	Mean deflection of the plumb-line Clarke-Bessel spheroid.			
		Referred to Kaliánpur as zero.		Referred to Kaliánpur as +6".	
Sub-Himalayan { mountains . . .	19	"	"	"	"
		- 33	± 1·24	- 27	± 1·25
plains . . . . .	23	- 3	± 0·87	+ 3	± 0·87
Zone of southerly deflection . . .	43	+ 3	± 0·26	+ 9	± 0·26
Indian Peninsula . . . . .	85	- 6	± 0·23	0	± 0·24
North-west India . . . . .	27	0	± 0·25	+ 6	± 0·24

We can now judge of the effects of the substitution of the Clarke-Bessel spheroid for EVEREST's by comparing the values given in the columns of Tables IV<sub>A</sub>, IV<sub>B</sub>, IV<sub>C</sub>, IV<sub>D</sub>, headed "Referred to Kaliánpur as zero," with the values given in Tables III<sub>A</sub>, III<sub>B</sub>, III<sub>C</sub>, III<sub>D</sub>. It will be seen that the large Himalayan deflections are slightly decreased, and that the positive tendency of the second region has been accentuated.

There is a marked difference between the values of Table III<sub>C</sub>. and the values "Referred to Kaliánpur as zero" in Table IV<sub>C</sub>. The progressive decrease in the observed deflections, from latitude 24° to latitude 8°, as exhibited on the spheroids of EVEREST and of CLARKE, had led me to believe that the direction of gravity throughout Peninsular India was being influenced by some external excess or deficiency of mass, such as the Himalayas or the Indian Ocean.\* The southerly deflections, shown in Table III<sub>C</sub>., at the extreme south of India, were attributed by General WALKER to the condensation of submarine strata.† The introduction of the Clarke-Bessel spheroid eliminates at once both the progressive decrease and the supposed southerly deflections in South India, and substitutes for them throughout the peninsula a large apparent northerly deflection averaging 6". The introduction of the Clarke-Bessel spheroid shows that the progressive change exhibited by Table III<sub>C</sub>. in the inclination of the level to the spheroidal surface from latitude 24° to latitude 8° was due, not, as I had supposed, to the deformation of the level surface, but to the abnormal curvature of the surface of EVEREST's spheroid.

\* Professional Paper No. 5 of 1901, "Survey of India;" Monthly Notices, 'Royal Astronomical Society,' January, 1902.

† 'Phil. Trans. Roy. Soc.,' vol. 186, 1895.

(6.) *The Zero of Verticality.*

Tables IVA., IVB., IVc., IVd., and IVe. show in terms of the old datum, namely, with Kaliánpur as zero, the angles of inclination in the meridian that have been determined in different parts of India between the level surface and the surface of the Clarke-Bessel spheroid. The *difference* between any two of these angles of inclination is affected only by changes of spheroid, but the absolute value of every angle is based on the assumption that the level and spheroidal surfaces are parallel at Kaliánpur. Any alteration in the assumed inclination of the two surfaces at this our initial station will affect the inclinations as deduced at other stations by a constant quantity. The direction of gravity at Kaliánpur has been adopted by the Survey of India as the datum, from which deflections of the plumb-line at all stations are measured; the direction of gravity is, we know, always perpendicular to the level surface; at Kaliánpur it has been assumed to be perpendicular to the spheroidal surface also. I propose now to deduce a new value for the deflection of the plumb-line at Kaliánpur, and to exhibit the values of the deflections of the plumb-line in India that will be obtained, if the deduced direction of gravity at Kaliánpur be substituted for the original one—in other words—if our zero or datum be corrected.

The direction of gravity throughout the first, second, and fourth regions appears to be under the influence of abnormal attractions; there is, I believe, no other area in the world in which the deflection of the plumb-line undergoes at once such large and such systematic variations as it does in the two first regions of Plate 15; these observed peculiarities, too, have been discovered to exist in the neighbourhood of extraordinary mountain masses, and though the connection between the observed phenomena and the visible protuberances is obscure, there can be little doubt that the latter are in some indirect way the cause of the former.

The direction of gravity in the fourth region also is probably influenced by the high mountains of Central Asia, though their effects are not directly perceptible. We will, therefore, omit from present consideration the results obtained in the first, second, and fourth regions, and we will confine our attention to those of the third region only.

The third region is in the form of a trigon with its apex at Cape Comorin; its length from north to south is 1100 miles, and its greatest breadth 1300 miles; its area is 750,000 sq. miles. This trigon is one of the oldest portions of land surface now existing on the earth; it is mostly composed of ancient gneiss, and though a large part was covered in the cretaceous period by volcanic overflows, it suffers now but slightly from earthquakes and is exceptionally stable. This trigon appears to be as free from abnormal sources of disturbance and to be as suitable for the determination of the absolute direction of gravity as any area of land can be. If we examine the results "Referred to Kaliánpur as zero" in Table IVc., we find that out of 85 determinations of the direction of gravity made within the third region, 80 show a

northerly deflection, two show a southerly deflection, and three show the direction of gravity to be vertical. The mean deflection throughout the trigon is  $6''\cdot4$  North.

Now if we are to accept these results as final, we shall have to believe that throughout the third region the level surface is always inclined by  $6''\cdot4$  to the spheroidal surface. We know of no cause tending to produce such an extraordinary deformation, and we are led to suspect the reasoning by which its existence has been inferred. The only certain fact that has been brought to light by observation is that the plumb-lines in the trigon have a northerly deflection greater by  $6''\cdot4$  than the plumb-line at Kaliánpur. We have, however, taken a step in advance of this safe ground, and have assumed that the direction of gravity at Kaliánpur is vertical, and that consequently the plumb-line throughout peninsular India is deflected  $6''\cdot4$  towards the north. Would it not be more reasonable to assume that the mean direction of gravity throughout the third region is vertical, and that the plumb-line at Kaliánpur is deflected  $6''\cdot4$  towards the south? The assumption of a southerly deflection of  $6''\cdot4$  at Kaliánpur will lead then to the conclusion that throughout the third region the level surface remains generally parallel to the spheroidal surface.

From visible evidence Kaliánpur, situated as it is in flat plains, would be adjudged a suitable datum station, but it unfortunately lies in the zone of southerly deflection, and its plumb-line is thus exposed to the horizontal attractions of hidden masses.

If our geodetic operations had been confined to the third region, and if our datum station had been originally selected within this region, we should not have been led to suppose that its whole area of 750,000 sq. miles was abnormally affected. If we had subsequently extended our operations to Kaliánpur, we should have discovered there a southerly deflection of about  $6''$ , and this we should have adopted without question.

TABLE showing the Number of Observed Deflections in the Third Region—

Lying between—	If we assume that the meridional deflection at Kaliánpur is—	
	0 .	+ $6''$ (south).
– $12''\cdot5$ and – $14''\cdot5$	2	0
– $10''\cdot5$ „ – $12''\cdot5$	7	0
– $8''\cdot5$ „ – $10''\cdot5$	13	0
– $6''\cdot5$ „ – $8''\cdot5$	18	2
– $4''\cdot5$ „ – $6''\cdot5$	23	5
– $2''\cdot5$ „ – $4''\cdot5$	10	15
0 „ – $2''\cdot5$	8	22
+ $2''\cdot5$ and 0	4	24
+ $4''\cdot5$ „ + $2''\cdot5$	0	9
+ $6''\cdot5$ „ + $4''\cdot5$	0	6
+ $8''\cdot5$ „ + $6''\cdot5$	0	2
Total . . . .	85	85

The southerly deflection at Kaliánpur of  $6''\cdot4$ , which has been deduced from plumb-line observations, is to a certain extent corroborated by the section drawn in Plate 14, fig. 3, from pendulum observations; if we assume that the errors in BASEVI's pendulum results will be found constant, the section will be raised with reference to the sea-level, but will not be otherwise affected; and if we regard the distribution of mass exhibited by this section, and calculate the deflection at Kaliánpur by means of CLARKE's formula ('Geodesy,' p. 298),

$$A = \rho \log_e \left\{ \left( \frac{c'}{b'} \right)^{c' \sin 2\sigma'} \cdot \left( \frac{c}{b} \right)^{c \sin 2\sigma} \cdot \left( \frac{b'}{b} \right)^{2h} \right\} + 2\rho \{ c' \phi' \sin^2 \sigma' - c \phi \sin^2 \sigma \},$$

we obtain a value of  $+5''\cdot1$ .\*

In Tables IVA., IVB., IVc., IVd., IVe., in the columns headed "Referred to Kaliánpur as  $+6''$ ," the values of deflections have been exhibited on the assumption always that the plumb-line at Kaliánpur is deflected  $6''$  towards the south.

#### (7.) Summary.

A comparison of the two values given to each deflection in Tables IVA., IVB., IVc., IVd., and IVe. will illustrate the effects of the adoption of the corrected datum; the large Himalayan deflections, it will be seen, have been slightly decreased; they amount now to about half the theoretical values derived from an application of the law of gravitation to the visible mountain masses; the sudden diminution of the large deflections at the foot of the mountains is still very remarkable.

The great zone of southerly deflection has been expanded both to the north and to the south, and it now includes many of the stations classified in the first and third regions; for instance, in the sub-Himalayan region (Table IVA.), the stations of Kaliana, Bansgopal, Jarura, and Jalpaiguri exhibit southerly deflections when the corrected datum is used; in the Indian Peninsula (Table IVc.) the positive zone has been extended southwards to Thikri, Ladi, Hathbena, and Chandipur; in North-west India (Table IVd.) *every station now presents a marked southerly deflection*; and the positive character of the deflections in the positive zone itself (Table IVB.) has been *strongly accentuated*.

To the north of the second and fourth regions stand the mountain masses of Central Asia, but throughout those regions the direction of gravity is systematically deflected towards the south. That the direction of gravity should be deflected everywhere towards the south with a mean inclination of  $8''$  throughout an area of half a million square miles (Tables IVB. and IVd.) is an extraordinary phenomenon of nature, and this phenomenon has been observed on flat low-lying plains bounded

\* Attraction at Station 24 of mass lying north of Station 38 =  $1''\cdot61$

" " 24 " " south " 38 =  $6''\cdot67$

$\frac{1''\cdot61}{6''\cdot67}$   
 $5''\cdot06$

on the north by mighty mountain ranges and tablelands. Deficiencies of density underlying and compensating the highlands, on whatever assumptions of depth they may be based, will be found insufficient to account either for the prevalence or magnitude of these southerly deflections; that the mountains and deflections are, however, in some way connected can hardly be doubted. The section in fig. 3 of Plate 14 perhaps justifies the inference that the general deflection of gravity towards the south is being caused by deficiencies, underlying not the mountains themselves, but the plains in the immediate vicinity of the mountains.

All our pendulum and plumb-line stations situated actually in the Himalayas have so far been located on peaks; the results deduced have therefore been obtained from the highest points in the several Himalayan districts visited. It is important that observations should be taken at stations situated in the deep valleys of the inner Himalayas. The difficulty of fixing such stations by triangulation has hitherto limited observations to summits, but it is necessary now that we should ascertain whether the subterranean deficiencies underlying the Himalayas vary in amount with the heights of the superincumbent mountains, or whether in their compensation of the mass as a whole they remain independent of the altitudes of the alternating ranges and valleys above (see fig. 2, Plate 14).

Another question of interest has arisen, namely, whether the southerly deflections of the second region merge gradually along the border line into the verticality of the third region, or whether there does not exist an intermediate longitudinal area in which northerly deflections prevail. A study of Table IVc. will show, I think, that throughout a strip immediately south of the dividing line the deflections have a tendency to be uniformly northerly.\* The cross-section in fig. 3 of Plate 14 shows an excess of mass to underlie Kaliánpur (Station No. 24), and this excess is possibly a contributory cause both of the southerly deflections of the second region and the northerly deflections in the parallel strip. The continuance of similar deflections both to the east and to the west of Kaliánpur lead me to think that the pendulum observations of the future will furnish on all Himalayan meridians cross-sections similar to that given in the figure.

Geodetical observations have shown that the density of the earth's crust is variable, but they have not given any positive indication of the depths to which these observed variations extend. All calculations of the effects of subterranean variations in density and of mountain-compensation have, therefore, to be based on arbitrary assumptions of depth. The fact that the plumb-line seems generally to respond readily to results given by the pendulum, perhaps justifies the inference that the observed variations in the density of the earth's crust are not deep-seated. If an abnormal amount of matter exists in the crust near the surface, it will exercise direct effects upon plumb-lines and pendulums in the vicinity, but if it lies at a great depth, its effects, especially on plumb-lines, will be less perceptible.

\**Vide* stations Chania, Valvadi, Badgaon, Ankora and Mal,

We have not at present sufficient pendulum stations to warrant definite conclusions, but we can make use of those we have to test whether the observations of the intensity and direction of gravity tend to corroborate one another.\* The cross-section in fig. 3 of Plate 14 gives the result of pendulum observations at stations on the meridian of  $70^{\circ} 30'$ ; the direction of gravity at these and intermediate stations is shown referred to Kaliánpur as  $+6''$  in Table IVA. for all places north of latitude  $27^{\circ}$ , in Table IVB. for places near latitude  $25^{\circ}$ , and in Table IVC. for all places south of latitude  $24^{\circ}$ . We can therefore institute the following comparisons :—

- (1) The pendulum section would lead us to expect a large northerly deflection at Station 38, and Table IVA. shows that at this station (Dehra Dún) the deflection is  $29''$  north.†
- (2) From Station 38 to Station 24 the pendulum indicates a gradual increase in the density of the crust; the plumb-lines confirm this increase in a remarkable manner.
- (3) At Station 24 (Kaliánpur) the pendulum indicates the existence of a greater amount of subjacent matter than underlies the stations on either side of it. Tables I. and II. show this more clearly than the section. Now, if we look in Table IVB., we find that from Kesri to Tinsia the plumb-lines are all deflected south *towards* Kaliánpur, whilst if we look in Table IVC. we see that from Takalkhera to Badgaon the plumb-lines are deflected north *towards* Kaliánpur. Thus the existence of an excess of matter in the crust indicated by the pendulum at Kaliánpur is confirmed by the action of the plumb-lines on both sides of it.
- (4) The pendulum section shows a considerable excess of matter to underlie Stations 6 and 7 (Bangalore). Now, if we look at Table IVC., we see that the direction of gravity is much disturbed in the neighbourhood of Bangalore. At the two base-line stations near Bangalore, the deflections are northerly; sixty miles north at Bommasandra the deflection is  $8''$  southerly. The inference is that an intermediate excess of matter exists, and that a station could be found north of Bangalore at which the pendulum would indicate a greater excess than at Bangalore itself. (The section had to be drawn from station to station, but if intermediate observations were to be taken, it is certain that the maxima and minima of the section would be slightly moved.)
- (5) Table I. shows that the force of gravity was below normal at all BASEVI's inland stations but Calcutta; for this reason Calcutta has hitherto been

\* It is true that the results of the old pendulum observations are not correct, but their errors are mainly systematic and though affecting absolute values do not vitiate differences. Differences are sufficiently accurate to justify the comparisons instituted.

† The names of the numbered stations of the section are given in Table II.

classified as a coast station. It is, however, 100 miles from the coast and is in truth less of a coast station than Kew or Greenwich. It was probably included amongst coast stations because BASEVI obtained there a positive result which accorded with his results at Madras and Bombay. But his positive result will, I think, be found in the future to be due not to Calcutta's proximity to the coast, but to her situation over the long chain of excessive density that is believed to run parallel to the Himalayas from west to east, and that is indicated in fig. 3 of Plate 14 by the position of Station 24.\* If we examine the last columns of Tables IVB. and IVC., we see that the deflections are south at Calcutta and Dariapur, but north at Cuttack and Khundabolo.

- (6) If an observer working over the plains of Northern India were to trust only to his eye and his level, he would record the existence of a great mountain range to the north and of low hills or flat plains to the south ; if, however, he were to disregard the evidence of the eye and of level, and were to believe either his pendulum or plumb-line, he would come to the conclusion that he was standing between two mountain ranges, one of which, visible to the north, was rising abruptly out of the plains, whilst the other, invisible to the south, was slowly gaining in elevation for 300 miles.

I have taken several instances of abnormal pendulum results from Table I. and have found in each case a direct response from the plumb-lines at neighbouring stations. This conformity could hardly ensue if the variations in density extended to greater depths than 30 or 40 miles. Our results do not justify us in asserting that no deep-seated variations in density exist, but they do justify the belief that the variations in density which have been discovered are apparently superficial.

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\* When I write of the excessive density of the earth's crust, I am judging from local observations only. I mean, therefore, "excessive" compared with surrounding portions of the crust, and not with the mean surface density of the earth.

# SECTION of the EARTH'S CRUST IN UPPER INDIA on the meridian of 77° 30'

Fig. 1

Section of the surface of India as determined by levelling.

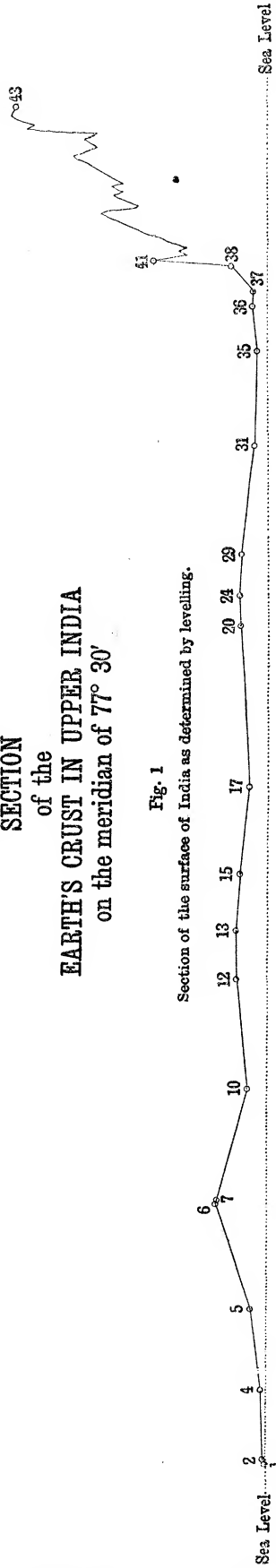


Fig. 2

Section deduced from Pendulum Observation showing the deficiency of matter in the Earth's crust.

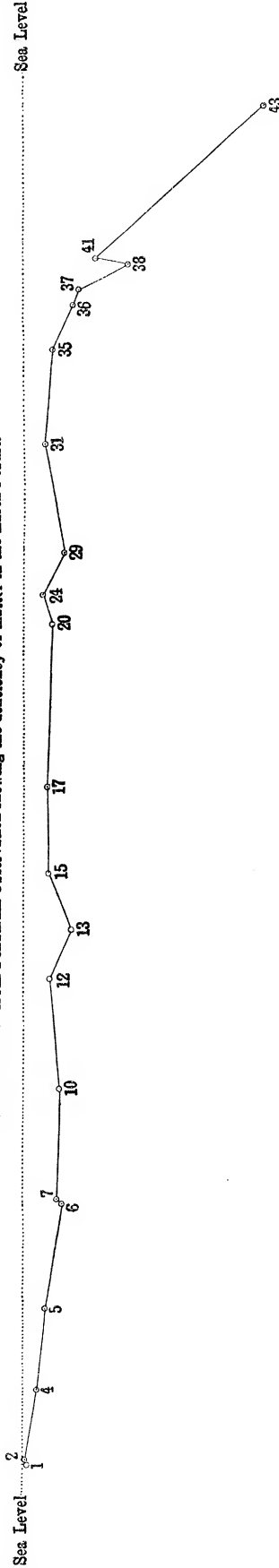


Fig. 3

Section of the surface showing the resultant amounts of matter underlying the several stations.

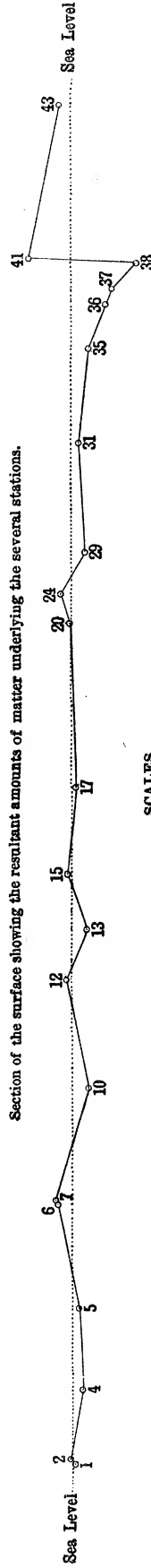
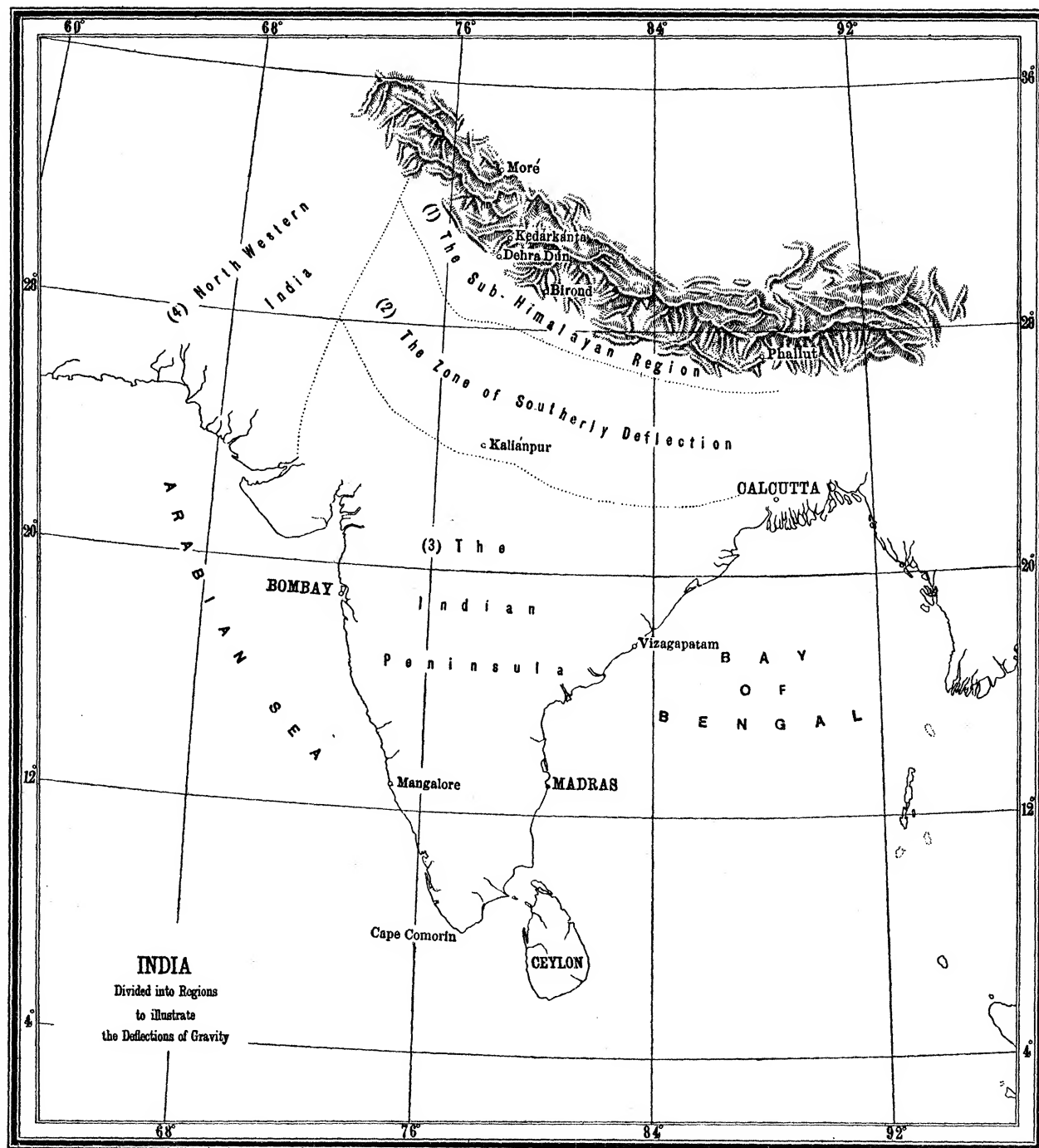
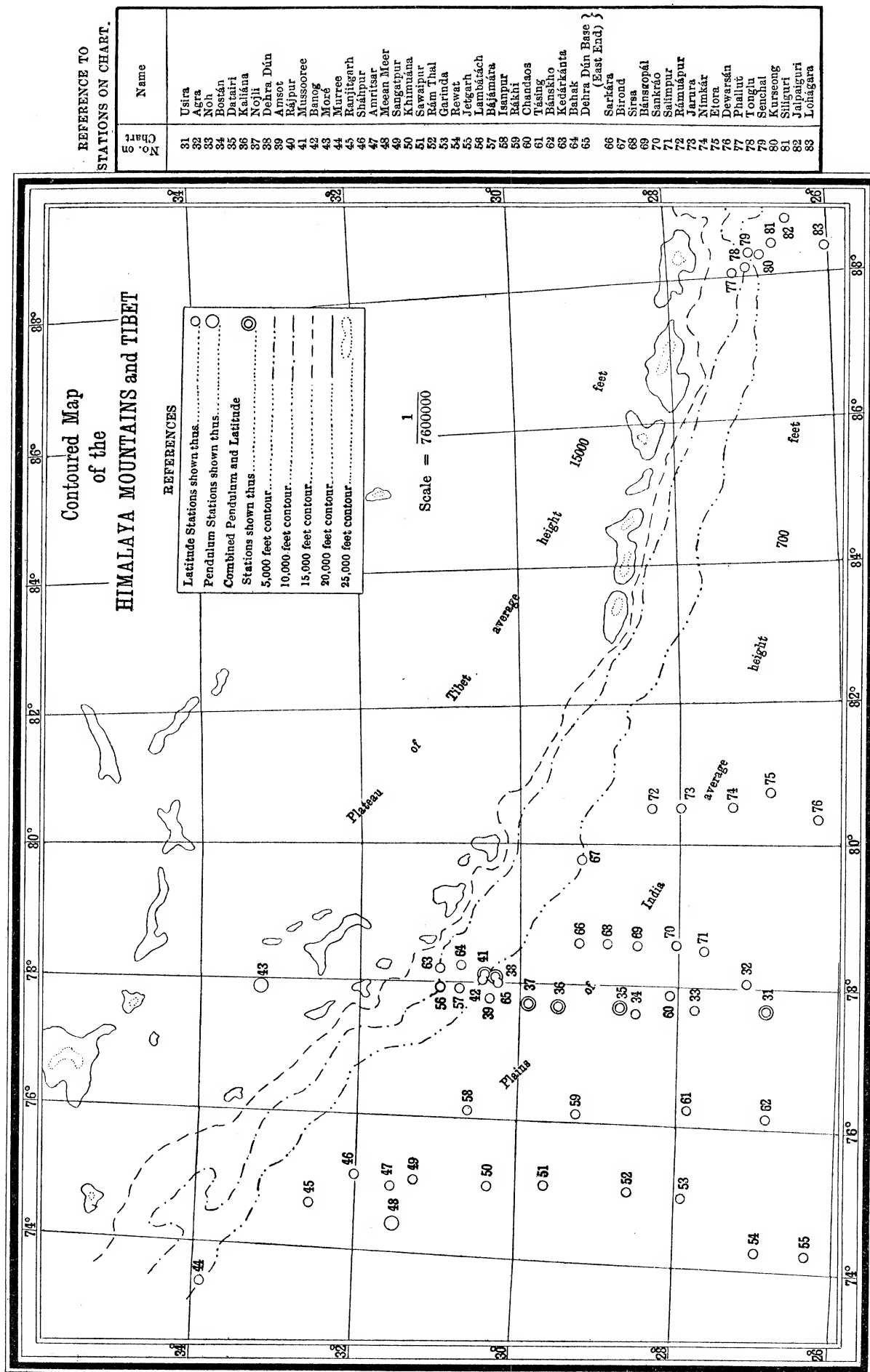


Fig. 3

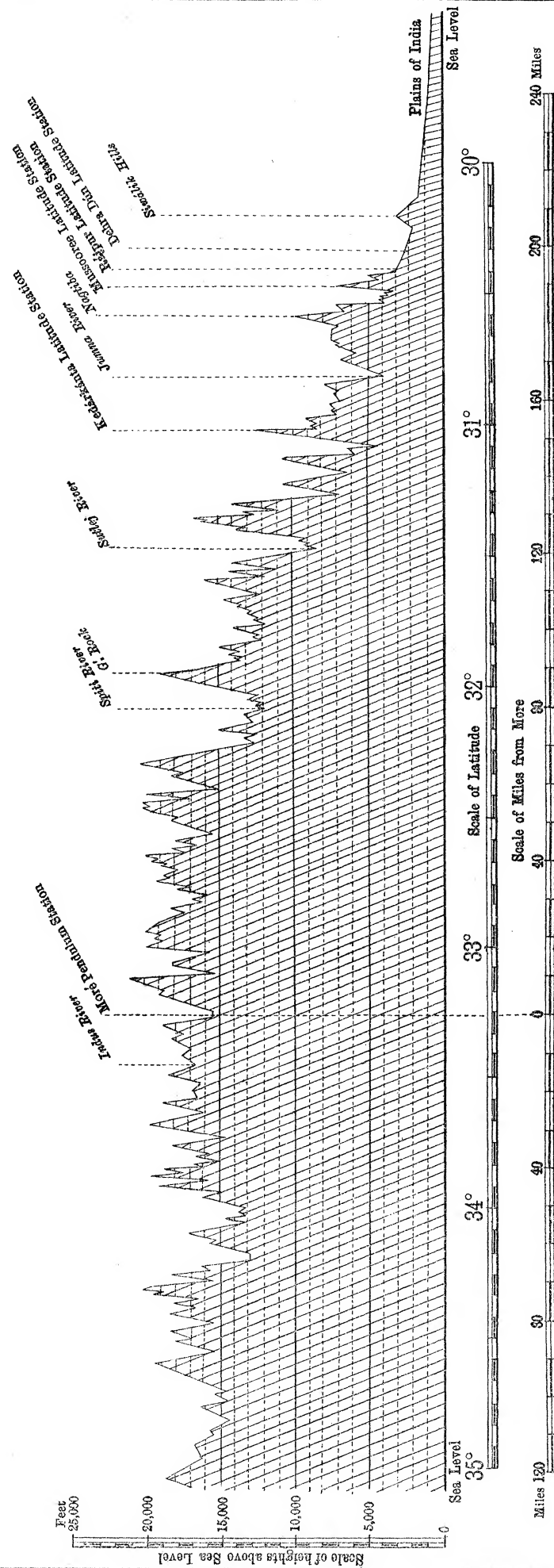
Horizontal  
1° of Latitude = 8 Millimetres  
or  
218 Miles = 1 Inch

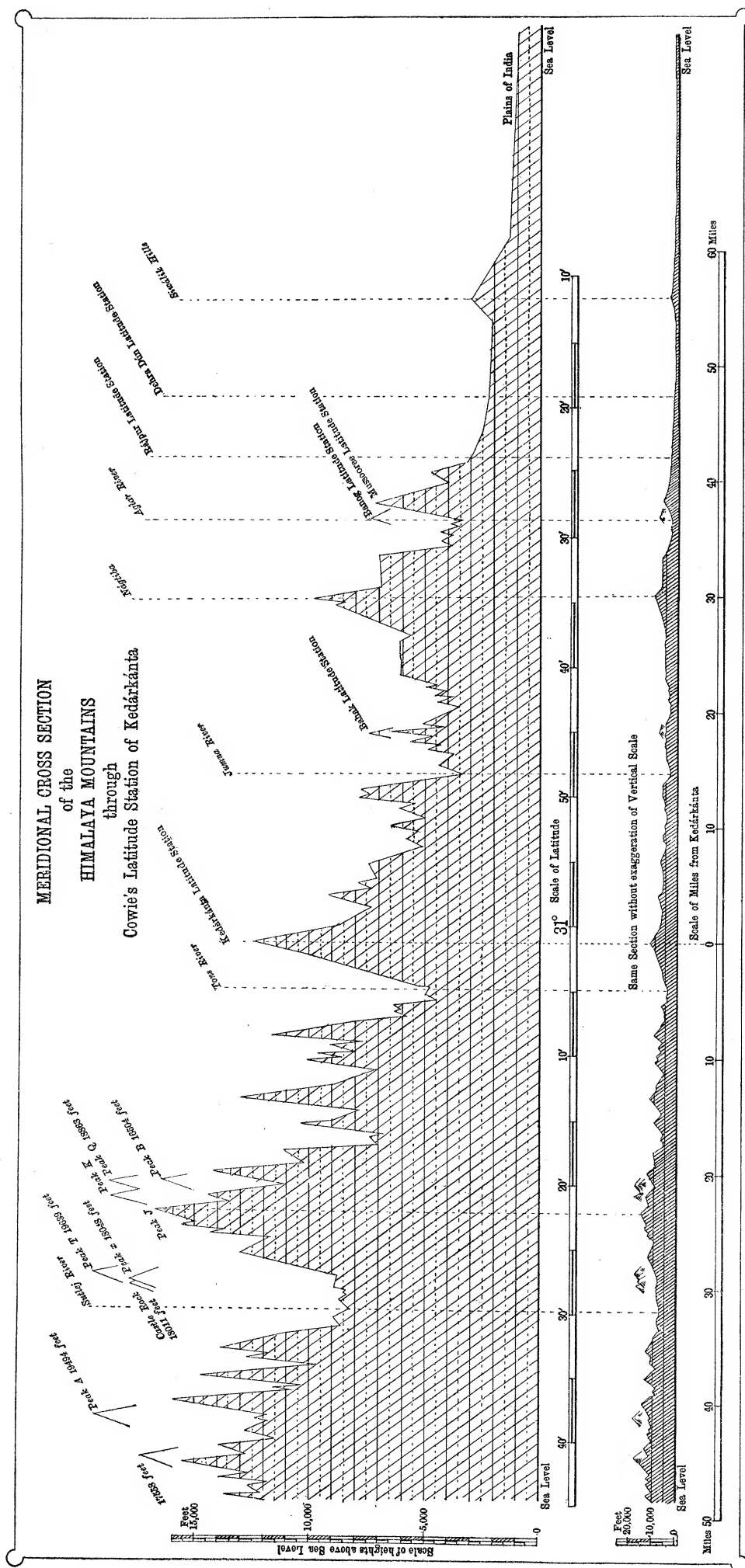
Vertical  
1,250 Metres = 1 Centimetre  
or  
10,420 Feet = 1 Inch



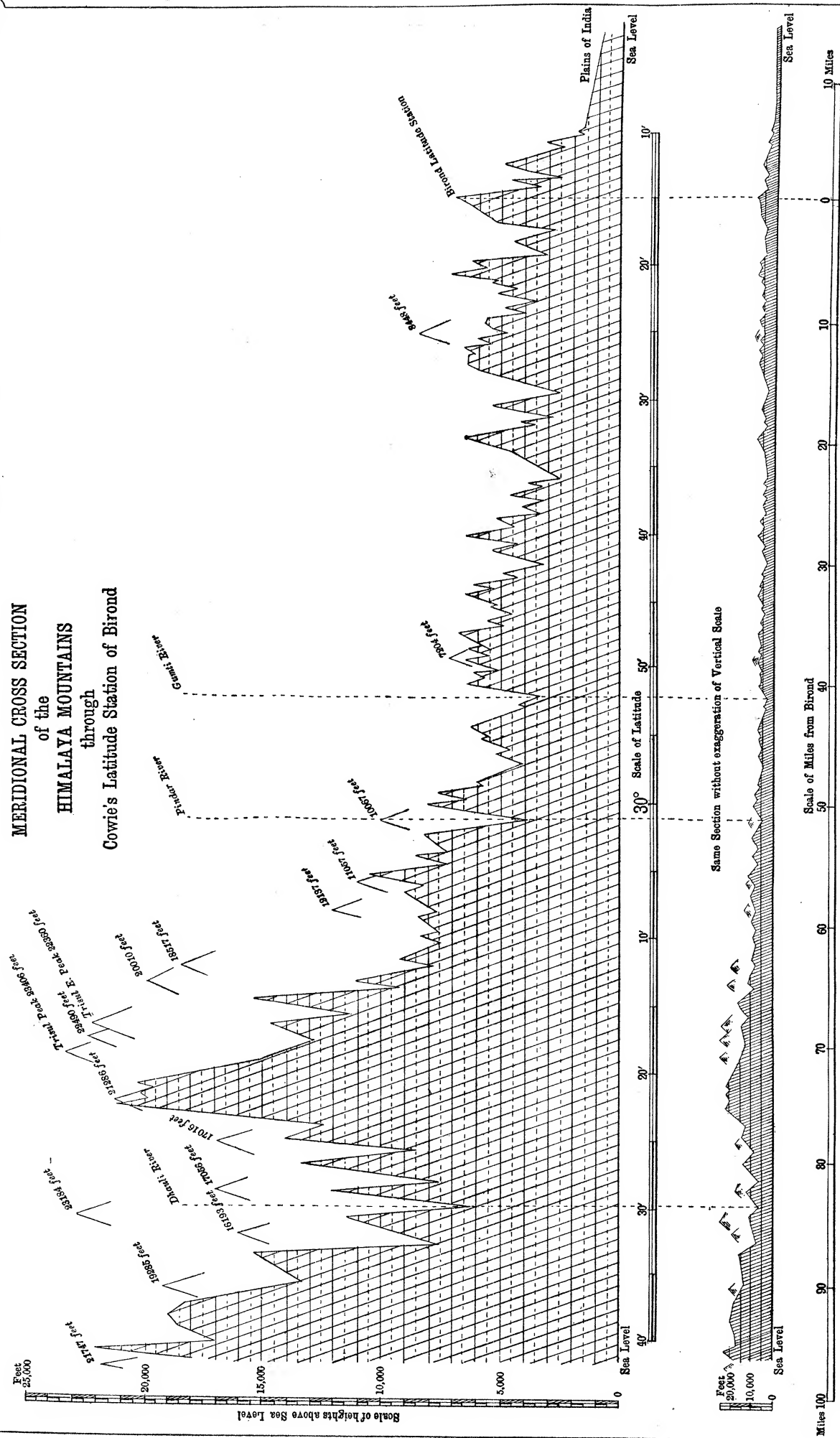


showing the  
Ranges intervening between Basevi's Pendulum Station of  
More' and Cowie's Latitude Station of Kedarkanta.





**MERIDIONAL CROSS SECTION  
of the  
HIMALAYA MOUNTAINS  
through  
Cowie's Latitude Station of Birond**



**MERIDIONAL CROSS SECTION**  
 of the  
**HIMALAYA MOUNTAINS**  
 through  
 Cowie's Latitude Station of Phallut

